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CFC Alternative Refrigerant Technologies

Estimated Retrofit and Replacement Costs for Army Air-Conditioning and Refrigeration Equipment Presently Using Chlorofluorocarbons

by
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Recent studies have verified that the emission of man-made chlorofluorocarbons (CFCs) into the atmosphere has depleted ozone in the stratospheric layer, and may affect terrestrial ecology. In response to actions intended to reduce or eliminate the production of CFCs, the Department of Defense (DOD) has issued a policy requiring minimal use of CFCs and halons.

Using baseline information calculated for the Army's air-conditioning and refrigeration (AC&R) equipment inventory based on site studies of three Army installations, information from the 1989 *Red Book*, and cost data from AC&R manufacturers, this study provides cost estimates for the replacement and/or retrofit of this equipment. A realistic estimate of the total cost of eliminating CFC use in Army facility AC&R equipment is \$150 million, based on expected retrofit of a portion of the inventory.

Retrofits may be more economical for relatively new equipment. However, the industry-wide guidelines necessary to implement large-scale refrigeration system retrofits are not yet available.



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FOREWORD

This research was performed for the U.S. Army Center for Public Works (USACPW), Fort Belvoir, VA, under project 4A162784AT45, "Energy and Energy Conservation," Work Unit EX-XM3, "CFC Alternative Refrigerant Technologies." The technical monitor was Chris Irby, CECPW-FU-M.

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ESTIMATED RETROFIT AND REPLACEMENT COSTS FOR ARMY AIR-CONDITIONING AND REFRIGERATION EQUIPMENT PRESENTLY USING CHLOROFLUOROCARBONS

1 INTRODUCTION

Background

The stratospheric ozone layer prevents most of the ultraviolet (UV) radiation from the sun from reaching the earth's surface. The ongoing depletion of this shield and increased UV penetration will profoundly affect the ecology of terrestrial life—likely resulting in increased skin cancer in humans as well as disturbing the balance of microorganisms that will ultimately affect the natural food chain. The depletion of ozone in the stratospheric layer and the identification of chlorofluorocarbon (CFC) refrigerants as contributors to this depletion has resulted in legislation mandating a phaseout of their production (U.S. Clean Air Act Amendment of 1990). In response to this requirement, the Department of Defense (DOD) issued a policy (DOD Directive 6050.9, 13 February 1989), the Army issued a letter (Headquarters, Department of the Army [HQDA] LTR 200-90-1, 27 July 1990), and the U.S. Army Center for Public Works (USACPW)* issued a Technical Note (TN 420-54-01, 26 June 1991), requiring minimal use of ozone-depleting substances and the elimination of their direct and unnecessary release into the atmosphere. Complete phaseout of CFC use in DOD is set for October 2000.

The large inventory of air-conditioning and refrigeration (AC&R) equipment owned and maintained by the U.S. Army uses a significant amount of the CFC refrigerants scheduled for phaseout. As a result, the Army is faced with the challenge of meeting the CFC regulatory requirements in a timely and economical manner within the context of rapidly developing alternative technologies. Eliminating the use of CFC refrigerants requires either their replacement with non-CFC equipment or conversion of existing equipment to non-CFC use. To help the Army meet this challenge, USACPW and the U.S. Army Construction Engineering Research Laboratories (USACERL) are working with industry to advance CFC alternative refrigerant technology and transfer the technology to the field.

Objective

The objective of this study is to provide an estimate of the cost of eliminating the usage of CFCs in AC&R equipment owned and maintained by the U.S. Army. The estimate includes the possibility of converting part of the existing equipment inventory with CFC refrigerants to the use of non-CFC refrigerants. The estimates obtained can be used to plan retrofit/replacement budgets and schedules and to identify specific areas for further studies.

Approach

As a first step in the Army's effort toward a timely and economic transition to non-CFC refrigerants, USACERL has compiled an Army-wide inventory data of AC&R equipment based on three U.S. Army

*The U.S. Army Center for Public Works is the former U.S. Army Engineering and Housing Support Center.

installations (Sohn, Homan, and Sliwinski) and AC&R inventory lists in the 1989 *Red Book*.^{**} In the present study, this inventory data and the cost data provided by AC&R equipment manufacturers are used to estimate the cost of converting or replacing all AC&R equipment presently using CFC refrigerants. Estimates produced by two U.S. Army Training and Doctrine Command (TRADOC) installations are compared with the estimates produced by the methodology presented in this report. Finally, the uncertainty in the cost estimate is analyzed to provide a realistic confidence level. Appendix A contains the Fiscal Year (FY)89 and FY90 *Red Book* AC&R inventory data for the Army by Major Command, and Appendix B has a detailed illustration of the calculation procedure used to arrive at the cost estimates.

Scope

This report estimates the retrofit and replacement costs necessary for elimination of CFC usage in Army facility AC&R equipment only. The Army's use of CFCs as solvents, firefighting agents, cleaning agents, in foam insulation, and as refrigerants in vehicle air-conditioning (AC) systems are beyond the scope of this report.

Mode of Technology Transfer

It is recommended that the information in this report be used to refine the DOD/DA policy on CFC issues such as development of criteria for conversion or replacement of CFC equipment. A portion of this draft report has been quoted for a briefing of the Assistant Secretary of the Army (ASA) for a policy development on budget programming. Portions of this report will be included in a Technical Bulletin for installation Directorate of Public Works (DPW) staff for developing their compliance cost estimate for the CFC-related regulations.

^{**} The *Red Book* is the common name for the *Facilities Engineering and Housing Annual Summary of Operations* (U.S. Army Engineering and Housing Support Center [USAEHSC], Fort Belvoir, VA).

2 ESTIMATION OF RETROFIT AND REPLACEMENT COSTS

The projections developed in this report are based on the study conducted by USACERL in cooperation with USAEHSC, *Chlorofluorocarbon Uses in Army Facility Air-Conditioning and Refrigeration* (Sohn, Homan, and Sliwinski). Results of the study included the determination of type, capacity, age, and refrigerant usage of AC&R equipment on Army installations. The study included collection of detailed equipment inventories from three typical Army installations (Fort Jackson, SC [TRADOC], Red River Army Depot, TX (U.S. Army Materiel Command [AMC]), and Fort Campbell, KY [FORSCOM]) and compilation of AC&R equipment data contained in the FY89 *Red Book* (refer to the USACERL report for a detailed description of the *Red Book*). The data obtained from the three site visits and the *Red Book* was used to project estimates of AC&R equipment age, capacity, and refrigerant usage for the entire Army.

Development of the projected retrofit and replacement costs will be presented in two separate sections, one for AC equipment and the other for refrigeration equipment. However, the general methodology used to arrive at the desired cost estimates is quite similar for both types of equipment. The approach used in this investigation is illustrated in Figure 1. The capacity data reported in the *Red Book* along with refrigerant and equipment usage data from the USACERL technical report [TR] FE-93/14 mentioned above are used to estimate the quantities of refrigerants used by AC equipment and the capacities of categories of refrigeration equipment. Then, with average equipment size data, the number of units using each type of refrigerant can be estimated. Finally, this information can be used with estimates of retrofit and replacement costs obtained from equipment manufacturers to estimate the compliance cost for the Army equipment inventory. Note that calculating the number of average-size units and multiplying by the cost per unit is equivalent to estimating the average cost per unit of capacity. However, the intermediate step of estimating the number of units clarifies the size of the inventory.

The Army-wide AC&R equipment inventory data as reported in the *Red Book* (1989,1990) is shown in Table 1. The data is reported in tons capacity.* Notice the slight increase in AC inventory capacity and the decrease in refrigeration inventory capacity from FY89 to FY90.

Air-Conditioning Equipment Methodology

The estimated total quantity of refrigerant used by AC equipment is the total capacity in tons multiplied by the average pounds of refrigerant per ton capacity. The ratio has been found to be approximately 2.0 lbs/ton for AC equipment. Using the total estimated quantity of refrigerant, the usage of each type of refrigerant can be calculated using the distribution shown in Table 2. These figures include the refrigerant used by all sizes of AC equipment. This approach has been used instead of directly using the *Red Book* data from each category since the USACERL TR FE-93/14 found that the AC capacities were often not listed in the correct categories. Refer to the TR for a further discussion of this.

The USACERL TR FE-93/14 found that only AC units of greater than 100 tons capacity used CFC refrigerants; units of less than 100 tons capacity used HCFC-22 (hydrochlorofluorocarbon-22) almost exclusively. Therefore it was assumed that all CFC refrigerants are being used by units having over 100 tons capacity. Some units of greater than 100 tons capacity were found to be using HCFC-22; at this time HCFC-22 is an acceptable refrigerant. However, the recently adopted Copenhagen amendments include a phaseout schedule for HCFC refrigerants beginning with a consumption freeze in 1996. The only unit

*1 ton = 12,000 Btu/hr; 1 lb = 0.454 kg

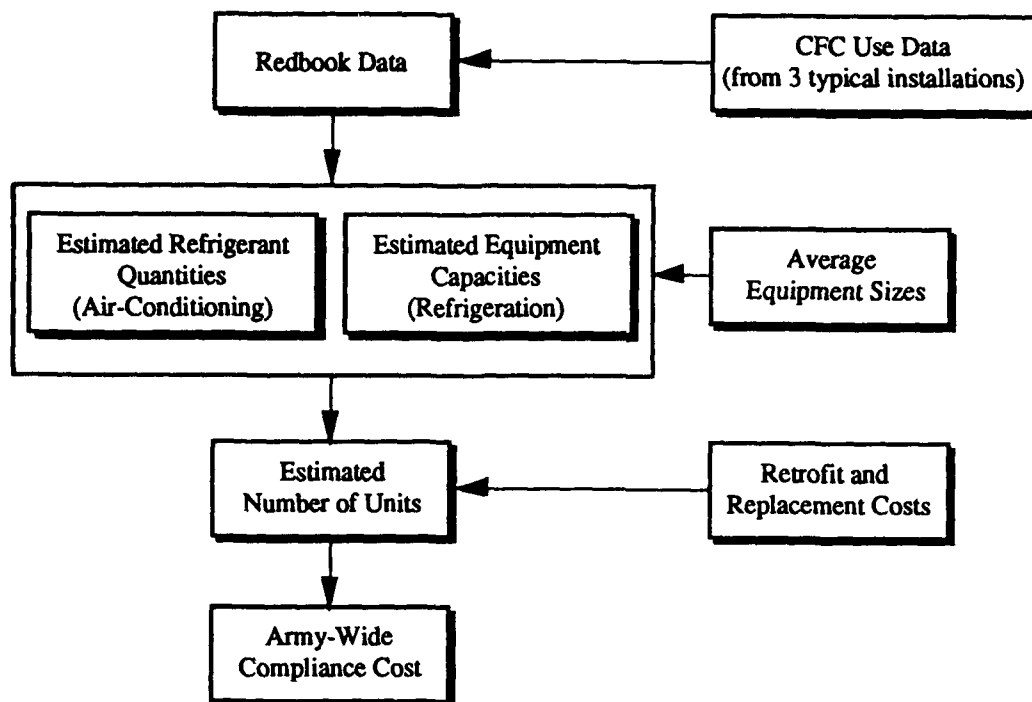


Figure 1. Methodology for Estimate of Compliance Cost.

with less than 100 tons capacity found in the usage study to be using a CFC refrigerant was a 99 ton R-502 unit located in a flight simulator at Fort Campbell. The effect of including this unit is seen in the small R-502 fraction shown in Table 2. Since this unit is very much an exception and the quantity is very small, the use of R-502 in AC equipment will be neglected. Equipment using R-500 will be considered as part of the equipment requiring retrofit or replacement since R-500 is an azeotropic mixture of CFC-12 (73.8 percent by mass) and R-152a (26.2 percent by mass).

The average size of machines using each of these types of refrigerants has been obtained from the Air-Conditioning and Refrigeration Institute (ARI) (Denny, August 1991) and is shown in Table 3. These sizes are consistent with the equipment observed at the three installations examined in the USACERL TR FE-93/14.

To convert the refrigerant quantities to capacity, the ratio of refrigerant charge to unit capacity is required. This ratio was obtained for units of greater than 100 tons capacity from data gathered during the site studies conducted as part of the USACERL TR FE-93/14. The lbs/ton ratio was calculated from a single parameter curve fit of the refrigerant charge and capacity of 18 large AC units. The calculation is illustrated in Figure 2. Notice that the average lbs/ton ratio is 2.2. This ratio is close to that used by many in the industry for this size of equipment, 2 lbs/ton. This similarity points to the accuracy of that study's calculation.

Calculation of the estimated number of chillers using each type of CFC refrigerant is now possible. The quantity of each CFC refrigerant is divided by the average chiller size for that refrigerant and the average lbs/ton ratio. One finds that chillers using CFC-11 make up a majority of the machines requiring either retrofitting or replacing. Determining the most cost-effective approach for meeting the CFC requirements of these machines will be of considerable benefit to the Army.

Table 1
U.S. Army AC&R Equipment Inventory Data*

Category	Capacity (FY89)	Capacity (FY90)
AC >100 tons	511,205	517,299
AC 26-100 tons	73,166	88,089
AC 5-25 tons	82,662	85,941
AC <5 tons	200,780	214,935
Heat pump	12,734	11,755
Total =	880,547 tons	918,019 tons
Cold Storage (hp)	25,029	20,375
Refrig >5 hp	85,091	81,930
Refrig <5 hp	15,985	18,586
Total =	126,105 hp	120,891 hp
*Source: FY90 Red Book, USAEHSC.		

Table 2
Breakdown of Refrigerant Usage in Air-Conditioning Equipment

Refrigerant	Fraction*
CFC-11	0.262
CFC-12	0.024
HCFC-22	0.612
CFC-113	0.003
R-500	0.098
R-502	0.001
*Source: Sohn, Homan, and Sliwinski.	

Table 3
Average Size of Chillers Using CFC Refrigerants

Refrigerant	Average Size*
CFC-11	550 tons
CFC-12	800 tons
CFC-113	220 tons
R-500	1300 tons

*Sources: ARI and Sohn, Homan, and Sliwinski.

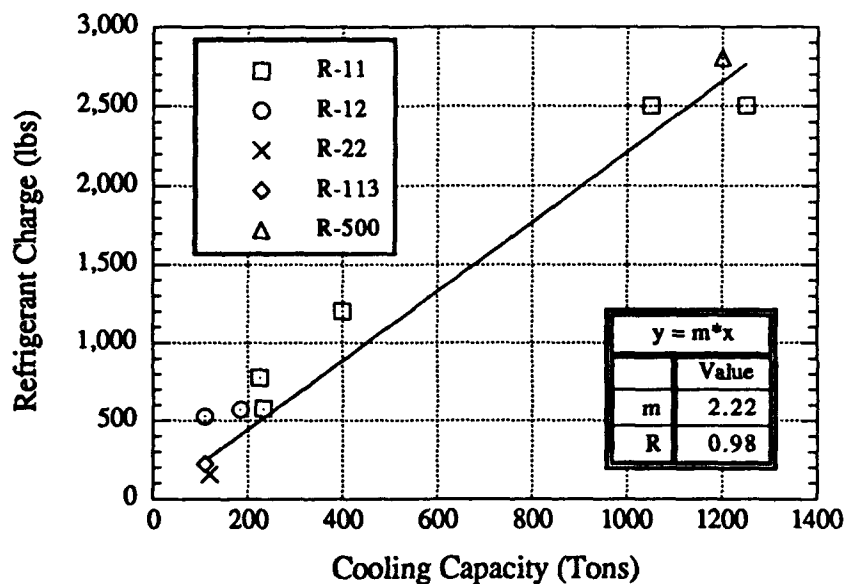


Figure 2. Refrigerant Charge vs Cooling Capacity.

USACERL TR FE-93/14 found that 75 percent of all AC equipment is less than 10 years old. This can be used as a first estimate for determining which units should be replaced or retrofitted. Units less than 10 years old can be assigned for retrofit and units greater than 10 years, for replacement. However, note that this may not be the optimum dividing point from an economic or practical standpoint for every installation. Therefore, this report presents the estimated costs for the complete range of replacement percentages, 0 to 100 percent. The issue of whether to retrofit or replace a particular machine is a local decision based on economics and technical considerations. Future studies can assist in this evaluation.

The alternatives available for AC equipment using each of the common refrigerants is shown in Figure 3. As stated earlier, units with a capacity of less than 100 tons use HCFC-22 almost exclusively, a refrigerant that regulations currently accept. For large chillers, the figure shows that it may be possible to retrofit units using CFC-11, CFC-12, or CFC-500. Units using CFC-113 will need to be replaced since the properties of CFC-113 (compared to the alternative refrigerants) make a retrofit impossible. Units using HCFC-22 can be left as is for now. Two AC equipment manufacturers have been contacted for estimates of the cost necessary to replace units typical of those used in the Army. Table 4 summarizes the cost estimates for the alternatives outlined in Figure 3. Note that the replacement costs shown are for equipment costs only. To account for installation costs, including labor, these figures are multiplied by

Table 4

Estimated Retrofit and Replacement Costs for Average Size Chillers

Existing Unit		Replacement		Retrofit	
Size	Refrig.	Cost*	Refrig.	Cost*	Refrig.
550 tons	CFC-11	\$160 - \$180	R-123/R-134a	\$35	R-123
800 tons	CFC-12	\$230 - \$250	R-123/R-134a	\$65	R-134a
220 tons	CFC-113	\$50 - \$100	R-123/R-134a	†	
1300 tons	R-500	\$250 - \$400	R-123/R-134a	\$85	R-134a

* Cost is given in thousands.

† Retrofit of this unit is not recommended.

a factor of 1.5 in this investigation—the installation cost is assumed to be 50 percent of the equipment cost.

In the current market, the Trane Co. is recommending refrigerant R-123 as an alternative for CFC refrigerants. R-123 has properties similar to CFC-11, making a retrofit of the CFC-11 chillers possible. The cost, however, varies depending upon the age and configuration of the machine (Wendl, January 1993). Retrofit of a CFC-11 machine could cost from \$5,000 to \$50,000. The lower end of the range is applicable for units less than 2 years old since many of these machines have been designed to be compatible with alternative refrigerants. The modifications necessary to retrofit such machines will be minimal. The price quoted in Table 4 for a retrofit is an estimate for a 5-year-old machine. Converting older machines to the new refrigerant will likely require replacement of all gaskets, a new impeller, replacement of motor varnish, and possibly even a new motor. Necessary modifications (and therefore

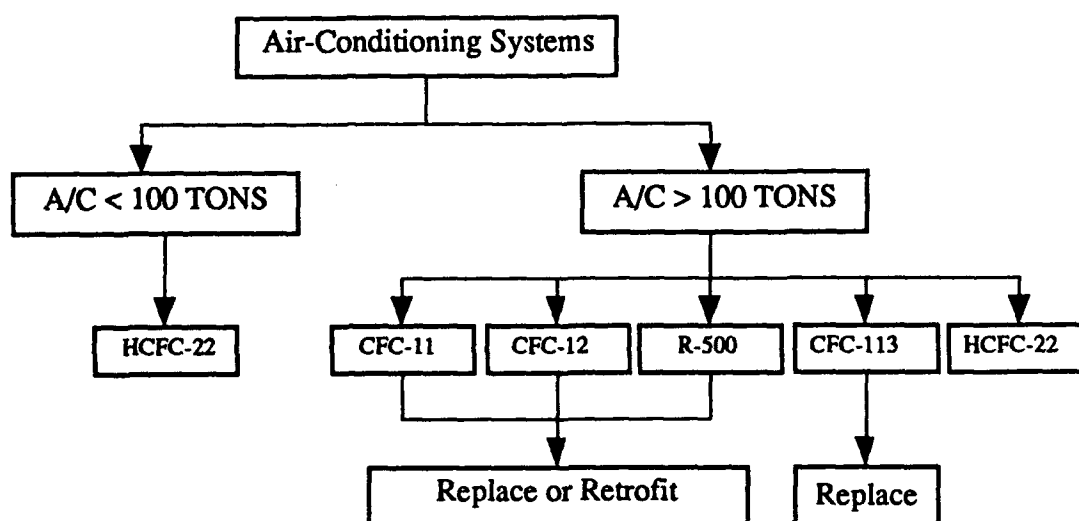


Figure 3. Retrofit and Replacement Options for Refrigerants Used in Air-Conditioning Systems.

cost) will depend on the age and configuration of the machine. Machines converted for use with a new refrigerant can also be expected to lose some capacity since the complete system is not optimized for the new refrigerant. The reduction in capacity could range from 5 to 20 percent.

Retrofit and replacement options have also been obtained from a McQuay Co. representative (Bilsland, January 1993). McQuay recommends R-134a as an alternative for CFC refrigerants. The cost for new machines using R-134a and retrofits to R-134a are as shown in Table 4. Both CFC-12 and R-500 machines can be retrofitted to R-134a. The ability to retrofit the large R-500 machines will result in considerable savings for the Army. The retrofit costs are only estimates, actual costs will vary depending on the age and configuration of the machine.

The cost for retrofit and replacement of existing equipment using CFC refrigerants can be calculated based on the cost information shown in Table 4, the estimated number of units, and the age summary from USACERL TR FE-93/14. Note that all CFC-113 machines have been assigned for replacement. It should be re-emphasized that the costs are for large chillers only (capacity greater than 100 tons). However, as mentioned earlier, these are the only units that need be considered for retrofit/replacement since almost all AC equipment of less than 100 tons does *not* use CFC refrigerants.

Cold Storage and Refrigeration Equipment Methodology

The inventory data reported in the *Red Book* is the basis for the estimate of retrofit and replacement costs of refrigeration and cold storage equipment using CFC refrigerants—the same as for AC equipment. The Army-wide cold storage and refrigeration (cold storage equipment has higher capacity hp than refrigeration) inventory data reported in the *Red Book* was previously shown in Table 1. The capacity data is given in horsepower (hp).*

The inventory study produced estimates of the refrigerant usage for all refrigeration equipment systems in the Army. The estimate includes refrigerant used by cold storage systems, large refrigeration systems (greater than 5 hp compressor), and small refrigeration systems (less than 5 hp compressor, including household refrigerators). Due to the different refrigerant use distribution for each of these groups, retrofit and replacement costs are estimated for each group separately.

Similar to the AC categories, USACERL TR FE-93/14 found that the two refrigeration categories were not representative of the installed inventory. The USACERL TR found that actual refrigeration capacity agreed better with the sum of the two categories, not the capacity reported in each category. Further discussion of this can be found in USACERL TR. As a result, the sum of the two refrigeration categories is divided using data obtained by the USACERL study. The breakdown is shown in Table 5. The household refrigerators are separated from the other refrigeration equipment because they need not be considered for retrofit or replacement even though they use CFC-12. This is due to the fact that household refrigerators rarely require repairs and the refrigeration system is hermetically sealed. Most often, they are run until they malfunction and are then replaced. Household refrigerators using R-134a will soon be available and can be used to replace existing units as they become inoperable.

Using the refrigerant distribution shown in Table 6, the estimated capacity of equipment using each type of refrigerant is calculated. CFC refrigerants are used in the majority of refrigeration and cold storage equipment.

*1 hp = 745.7 W.

Table 5
Breakdown of Refrigeration Capacity

	Fraction
Large refrig. units (>5 hp)	0.106
Small refrig. units (<5 hp)	0.126
Household refrigerators	0.768

*Source: Sohn, Homan, and Sliwinski.

The next step is estimating the number of units. The average size of units in each category has been determined from the equipment used at the three installations examined by USACERL. The average sizes are shown in Table 7. The estimated number of units using each type of refrigerant is found by dividing the total capacity by the average size of equipment in the category.

Using the same criteria as for AC, refrigeration units older than 10 years are assigned for replacement and units less than 10 years are to be retrofitted, if possible. Of the refrigeration units at the three installations studied by USACERL (TR FE-93/14), 90 percent were less than 10 years old. This suggests that a large number of units could be considered for retrofit instead of replacement.

The options available for equipment using each of the refrigerants are illustrated in Figure 4. All three types of equipment use CFC-12, CFC-502, and HCFC-22. Based upon discussions with equipment suppliers, it may be possible to retrofit CFC-12 units. Replacement of CFC-502 units has been assumed to be necessary, although some systems are being retrofitted with R-22, SUVA HP62, HP80, or HP81 in the private sector. Replacement prices from a local equipment supplier are shown in Table 8. Retrofit costs were estimated at 1/3 to 1/2 of replacement costs.

The cost of changing cold storage and refrigeration equipment to non-CFC refrigerants can be estimated using the above information. All R-502 units have been assigned for replacement because the alternative to R-502 is currently uncertain. It is unknown whether the R-502 replacement will be suitable for retrofitting existing machines. As for AC equipment, R-134a will be used as the CFC-12 replacement.

Table 6
Fractional Refrigerant Usage by Equipment Category

	CFC-12	HCFC-22	R-502
Refrigeration Units (Capacity <5hp)	0.792	0.02	0.188
Refrigeration Units (Capacity >5hp)	0.384	0.171	0.445
Cold Storage (including ice mfg.)	0.853	0.073	0.074

*Source: Sohn, Homan, and Sliwinski.

Table 7

Average Size of Refrigeration Equipment in Each Equipment Category

Category	Average Size*
Refrigeration (Capacity <5 hp)	2.5 hp
Refrigeration (Capacity >5 hp)	7.5 hp
Cold Storage (including ice mfg.)	35 hp

*These are the average sized units for the category as observed during the Sohn, Homan, and Sliwinski study.

Currently, new R-134a-based machines are becoming available on the market as are guidelines for the CFC-12/R-134a retrofit. Equipment manufacturers are conducting tests to determine the feasibility of this retrofit. Satisfactory results from these tests must predate any large-scale conversions of CFC-12 equipment to R-134a. These results will be important to the Army because of their savings potential.

Estimate of Total Costs

The Army's estimated cost of compliance with present CFC phaseout schedules was determined using the methodology presented in the previous paragraphs. An initial cost estimate can be made based on the assumption that the age of equipment examined during the inventory study is representative of the majority of equipment in the Army and that all equipment less than 10 years old can be retrofitted using

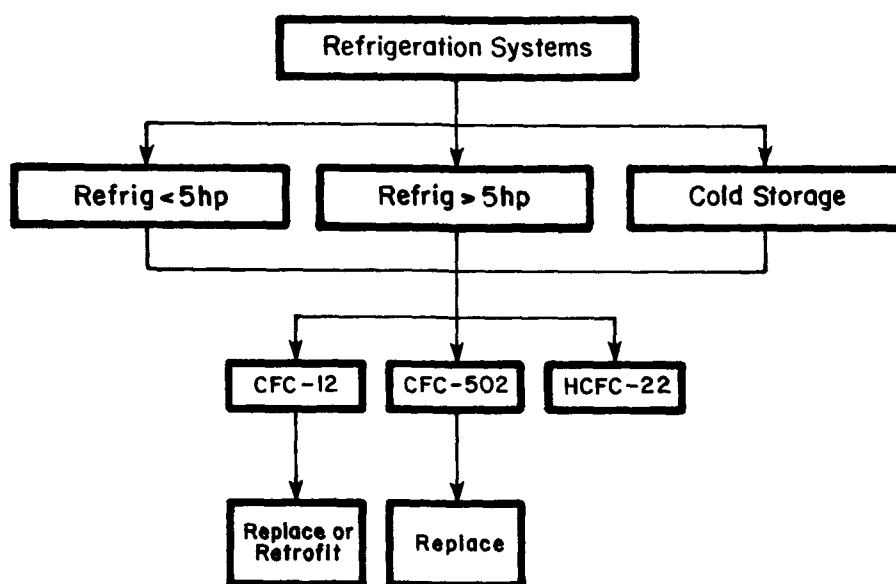


Figure 4. Retrofit and Replacement Options for Refrigerants Used in Refrigeration Systems.

Table 8

Estimated Replacement Cost for Average Size Refrigeration Units

COST			Explanation
2.5 hp unit	7.5 hp unit	35 hp unit	
\$1,500	\$3,500	\$20,000	basic system
+ \$500	+ \$500		misc. parts
\$2,000	\$4,000		
x 1.25	x 1.25		new refrig. increase
\$2,500	\$5,000		
+ \$2,000	+ \$2,500	x 1.5	installation
\$4,500	\$7,500	\$30,000	

the new refrigerants. Under these assumptions, and using FY89 data, the projected cost is \$76.8 million. Refer to Appendix B, Army-wide Retrofit and Replacement Cost Calculations, for tabular views of the calculation process.

However, the initial cost estimate is open to question given the uncertainty in the actual age of the Army equipment inventory and the undetermined dividing point between retrofit and replacement. Thus bounds for the total estimated cost can be calculated by examining the change in total cost with fraction of equipment replaced. This approach is useful since the estimated equipment age and retrofit/replacement dividing point only serves to define the proportions of the inventory that should be replaced and retrofitted.

The total cost for FY89 and FY90 inventory data and the separate cost for AC&R systems (FY89 data only) are shown versus replacement percentage in Figure 5. The total cost line, although it appears to be one line, is actually both the line for FY89 and FY90. The cost estimates using data from the 2 years are basically the same. The graph should be interpreted the following way: at 100 percent replacement none of the equipment using CFC refrigerants is retrofitted, and conversely at 0 percent replacement all CFC-based equipment (using refrigerants that can be retrofitted) is retrofitted. Some of the equipment will be suitable for retrofit, the majority will require replacement. In Figure 5, the lower bound on the total cost is approximately \$45 million and the upper bound approximately \$190 million. The lower bound will not be reached because some units will have to be replaced. The initial cost estimate of \$76.8 million, viewed in light of the information shown in Figure 5, appears quite optimistic.

A more realistic estimate of the total cost of *eliminating* CFC use in Army facility AC&R equipment is \$150 million. This is a realistic estimate since part of the inventory will likely be retrofitted, although the extent will be dependent on retrofit/replacement strategy, market conditions, and the actual condition of the AC&R equipment inventory.

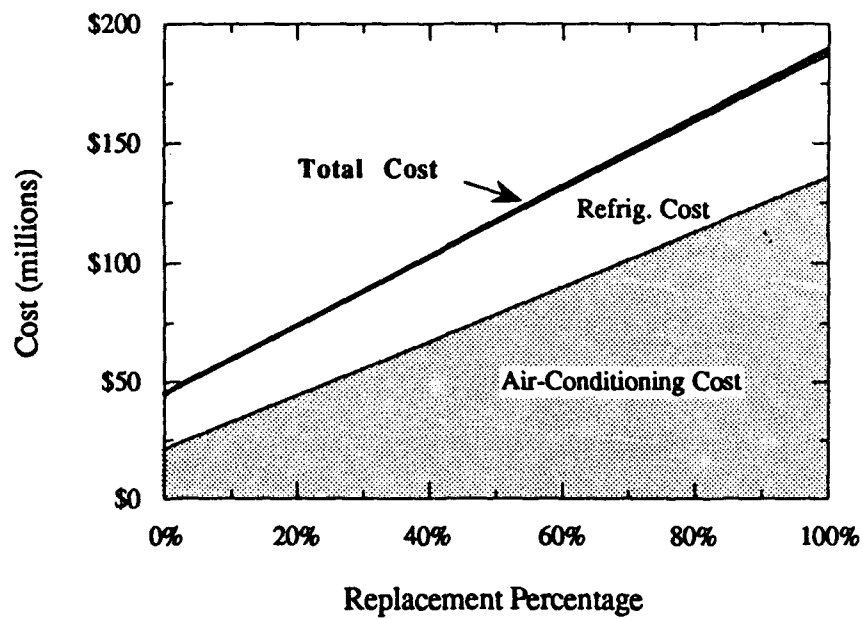


Figure 5. Estimated Retrofit and Replacement Costs vs Replacement Percentage.

3 COMPARISON WITH EXISTING ESTIMATES

In this chapter, comparisons are made between cost studies various installations conducted themselves and estimates produced by the methodology presented in this report. These comparisons are valuable for verifying the acceptability of the estimates obtained in the present study. However, the comparisons should be viewed within the context of the uncertainties in both the installation cost studies and the estimates presented in this study. Recall that the basis of the estimates in this report are the data contained in the *Red Book*, combined with equipment data from three of the nearly 200 Army installations, and estimates of retrofit and replacement costs for average size units obtained from equipment suppliers. The present study uses generalizations to arrive at an overall result for the Army, and therefore can be expected to produce inexact numbers at the installation level. Installation studies, although conducted with exact equipment inventories, use equipment prices in their calculations that are not contracted prices. The prices can vary and fluctuate. In addition, their studies were conducted a few years ago, and therefore, may not reflect current equipment prices.

Fort Leonard Wood

A CFC-phaseout plan has been developed by personnel at Fort Leonard Wood, MO (U.S. Army Training and Doctrine Command [TRADOC]). The plan lists the estimated costs for replacement of all equipment using CFC refrigerants. The costs included in the phaseout plan are shown in Table 9.

The equipment categories shown in Table 9 are different than those used in the present study. However, the first two categories are the same as those used in this study, and are compared first. The comparison is illustrated in Figure 6. The figure shows the estimates obtained using the methodology of this report for the two categories, (1) AC and cold storage and (2) all AC, cold storage, and refrigeration equipment. The difference between the two is very small because the amount of refrigeration capacity reported by Fort Leonard Wood in the *Red Book* is rather small. The inventory data reported in the *Red Book* for Fort Leonard Wood is shown in Table 10. The bubble in Figure 6 indicates the estimated cost for replacement of chilled water and cold storage systems reported in the Fort Leonard Wood study. The Fort Leonard Wood estimate is adequately bounded on either side by the study estimate range.

Table 9

Fort Leonard Wood CFC Phaseout Plan Cost Estimates

Equipment Description	Estimated Cost
Chilled water systems (AC)	\$1,825,000
Cold storage units	\$480,000
Commercial refrigerators, ice machines, freezers	\$550,000
Walk-in coolers, freezers	\$120,000
Ice water, beverage, food counters	\$330,000
Air dryers	\$227,000
Total = \$3.5 million	

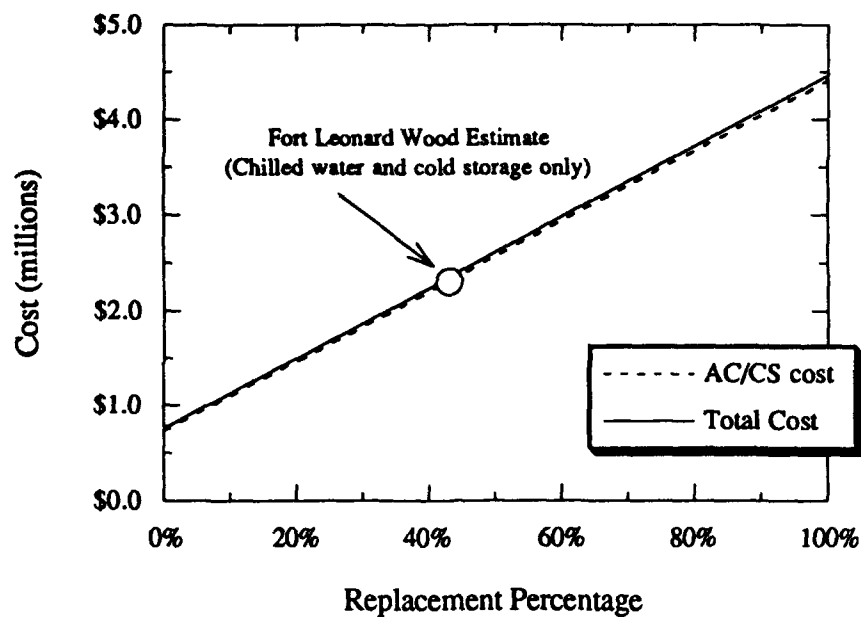


Figure 6. Estimated Replacement and Retrofit Costs vs Replacement Percentage for Fort Leonard Wood.

Table 10

Fort Leonard Wood AC&R Inventory Data*

Category	Capacity
AC >100 tons	8,900
AC 26-100 tons	4,500
AC 5-25 tons	2,517
AC <5 tons	9,047
Heat pump <5 tons	60
Total =	25,024 tons
Cold Storage (hp)	330
Refrig >5 hp	
Refrig <5 hp	215
Total =	545 hp

* Source: FY90 Red Book, USAEHSC.

The next comparison is one of overall costs. The total estimated cost reported in the Fort Leonard Wood study is \$3.5 million. The total estimated cost calculated by the method of this report is \$4.5 million (100 percent replacement). The two estimates do not include the same equipment and not all of the equipment included in the Fort Leonard Wood study needs to be replaced. Units such as beverage, food counters, ice machines, and commercial refrigerators are often hermetically sealed and rarely develop leaks. Exclusion of these units would narrow the gap between the two estimates, providing an even more favorable comparison.

Fort Jackson

A report titled *CFC Reduction Study and Procedures for Selected Facilities* was completed in June 1991 by PM&A Consulting Engineers under contract to USACE, Savannah District. The study included an inventory of AC&R equipment at Fort Jackson, a schedule for the replacement of CFC refrigerants in use, and cost estimates for replacement/retrofit of the major AC&R systems. The cost estimates included in the study are shown in Table 11.

Similar to the approach used for the Fort Leonard Wood estimates, the *Reduction Study* results can be compared to the estimate from the present study. The *Red Book* data used to calculate the cost estimate for Fort Jackson is shown in Table 12. The comparison between the estimates is shown in Figure 7. The broken line is the cost for AC, cold storage and refrigeration (greater than 5 hp only). The solid line is the cost for all equipment using CFCs. The *Reduction Study* estimate includes nearly the same equipment as that indicated by the broken line and is shown as the bubble on this line. The *Reduction Study* estimate does not include approximately two-fifths of the refrigeration capacity greater than 5 hp. Inclusion of this refrigeration capacity would bring the *Reduction Study* estimate to roughly \$1 million. Figure 7 shows that the *Reduction Study* is within the estimate range of the present study.

Table 11

Fort Jackson CFC Reduction Study Cost Estimates

Equipment Description	Estimated Cost
Chilled water systems (AC)	\$494,000
Cold storage units	\$67,000
Refrigeration units > 5 hp capacity	\$204,000
	Total = \$765,000

Table 12
Fort Jackson AC&R Inventory Data*

Category	Capacity
AC >100 tons	12,031
AC 26-100 tons	~
AC 5-25 tons	~
AC <5 tons	3,001
Heat pump <5 tons	~
Total =	15,032 tons
Cold Storage (hp)	525
Refrig >5 hp	1,054
Refrig <5 hp	~
Total =	1,579 hp

*Source: FY89 Red Book, USAEHSC.

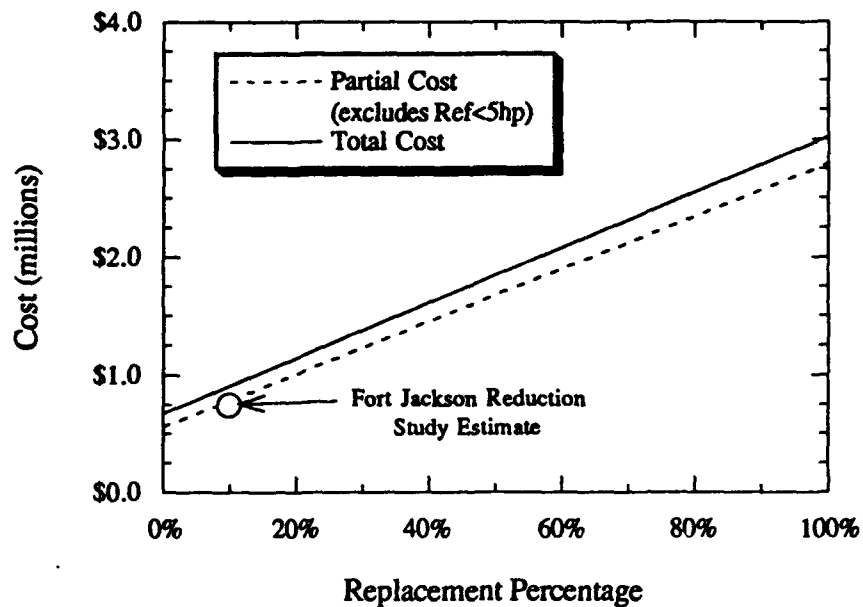


Figure 7. Estimated Replacement and Retrofit Costs vs Replacement Percentage for Fort Jackson.

4 ANALYSIS OF ESTIMATE UNCERTAINTY

The estimated costs for elimination of CFC refrigerants in facility AC&R systems were examined as a function of replacement percentage since the actual condition of the entire Army inventory is unknown. In this chapter, the uncertainty in the cost estimate as a function of replacement fraction is examined. The purpose is to provide a realistic confidence interval for the estimate. The analysis follows a method presented by Coleman and Steele (1989).

Consider a general case in which a result, r , is a function of J variables X_i :

$$r = r(X_1, X_2, \dots, X_J) \quad [\text{Eq 1}]$$

then the uncertainty in the result, U_r , is given by:

$$U_r = \left[\left(\frac{\partial r}{\partial X_1} U_{x_1} \right)^2 + \left(\frac{\partial r}{\partial X_2} U_{x_2} \right)^2 + \dots + \left(\frac{\partial r}{\partial X_J} U_{x_J} \right)^2 \right]^{1/2} \quad [\text{Eq 2}]$$

where the U_{x_i} are the uncertainties in the variables X_i .

The total cost for elimination of CFCs in AC equipment is given by:

$$\text{Total Cost} = \sum_{i=1}^3 g c \frac{p_1}{p_2} \frac{n_i f_i}{s_i} + \sum_{i=1}^3 (1-g) c \frac{p_1}{p_2} \frac{r_i f_i}{s_i} + c \frac{p_1}{p_2} \frac{n_4 f_4}{s_4} \quad [\text{Eq 3}]$$

where the subscript i indicates the refrigerant type (CFC-11, CFC-12, CFC-500, or CFC-113). The first term on the right side of the equation is the replacement costs for CFC-11, CFC-12, and CFC-500 chillers, the second term is the retrofit costs for the same types of chillers, and the third term is the replacement costs for all CFC-113 chillers. The variables are defined as:

- c = total AC capacity given in the *Red Book*
- g = the fraction of equipment replaced
- p_1 = lbs/ton ratio for all AC equipment (2.0)
- p_2 = lbs/ton ratio for chillers (2.2)
- n_i = cost of replacing chiller using refrigerant i
- r_i = cost of retrofitting chiller using refrigerant i
- s_i = average size of chiller using refrigerant i
- f_i = fraction of AC capacity using refrigerant i

The total cost is therefore a function of the following variables:

$$\text{Total Cost} = f(c, p_1, p_2, n_j, r_j, f_j) \quad [\text{Eq 4}]$$

each of which has an associated uncertainty. The estimated uncertainties are shown in Table 13.

The total cost for elimination of CFCs in refrigeration equipment is given by:

$$\text{Total Cost} = \sum_{j=1}^3 g \frac{n_j b_{1j} c_j}{s_j} + \sum_{j=1}^3 (1-g) \frac{r_j b_{1j} c_j}{s_j} + \sum_{j=1}^3 \frac{n_j b_{2j} c_j}{s_j} \quad [\text{Eq 5}]$$

where the index j indicates the categories refig<5hp, refig>5hp, and cold storage. The first term on the right side of Equation 5 is the cost for replacement of CFC-12 machines, the second term is the retrofit of CFC-12 machines, and the third term is replacement of CFC-502 machines. The variables are defined as:

- g = the fraction of equipment replaced
- n_j = cost of new equipment in category j
- r_j = cost of retrofitting equipment in category j
- b_{1j} = fraction of equipment in category j using CFC-12
- b_{2j} = fraction of equipment in category j using CFC-502
- c_j = total capacity of equipment in category j
- s_j = average size of equipment in category j

where c_j is the *Red Book* refrigeration capacity multiplied by a factor, f_j , for refig<5hp and refig>5hp. For cold storage c_j is the capacity reported in the *Red Book*. Therefore, the total cost is a function of the following variables:

$$\text{Total Cost} = f(k, l, n_j, r_j, f_j, b_{ij}) \quad [\text{Eq 6}]$$

where k and l (see Table 14) are the *Red Book* refrigeration and cold storage capacities, respectively. The estimated uncertainties in each of the variables are shown in Table 14.

The uncertainty in the total cost for elimination of CFC usage in Army facility AC&R equipment is shown as a function of replacement percentage in Figure 8. The dotted lines indicate the extent of the region in which the true value is expected to fall based upon the uncertainties in the variables shown in Tables 13 and 14.

Table 13

Estimated Uncertainties in AC Cost Variables

Variable	Uncertainty
c	$\pm 75,000$ tons
p1, p2	$\pm 10\%$
ni, ri	$\pm 30\%$
fi	$\pm 20\%$

Table 14

Estimated Uncertainties in Refrigeration Cost Variables

Variable	Uncertainty
k	$\pm 15,000$ hp
l	$\pm 7,500$ hp
nj, rj	$\pm 30\%$
fi	$\pm 25\%$
rij	$\pm 20\%$

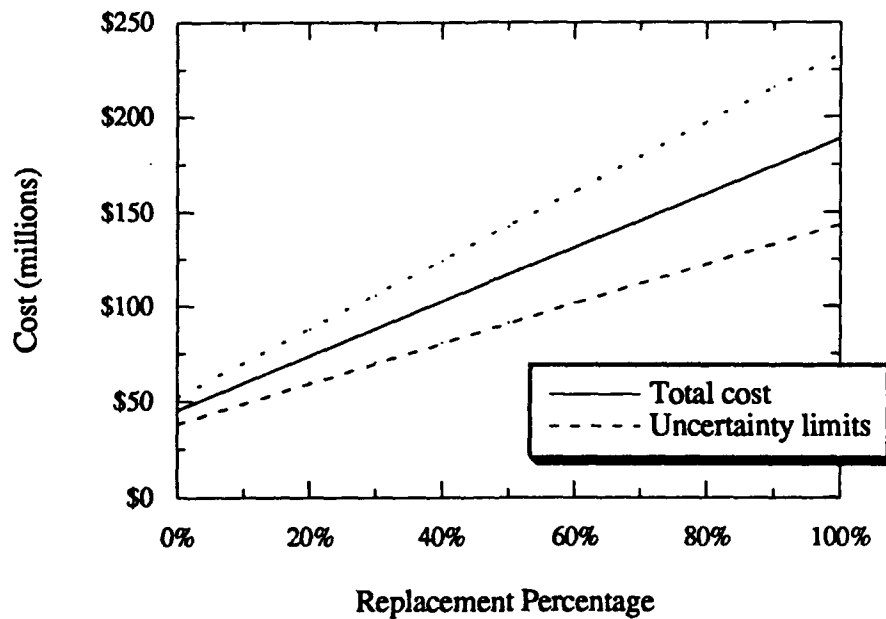


Figure 8. Estimated Limits of Uncertainty in Total CFC Elimination Cost.

5 CONCLUSIONS

Examining the data gathered from the 1989 *Red Book*, an inventory of three typical Army installations, and information from AC&R manufacturers, this study has calculated a range of cost estimates for the replacement and retrofit of Army AC&R equipment. The study concludes the following:

- AC equipment of less than 100 tons capacity uses HCFC-22 almost exclusively. This equipment does not need to be replaced now.
- Retrofit and replacement options for AC equipment are new technologies that are now available.
- Non-CFC alternatives for some refrigeration systems are now available.
- The industry-wide technical guidelines necessary to implement large-scale retrofits for refrigeration systems are not yet available.
- Refrigeration equipment such as commercial refrigerators and freezers need not be replaced since these units are typically hermetically sealed and rarely develop leaks. These units can be replaced at the end of their lifetime with CFC-free units.
- The total cost for elimination of CFC usage in Army facility AC and refrigeration equipment is \$190 million for *complete replacement* of existing equipment. A total cost of \$150 million is a realistic final estimate based on the expected retrofit of a portion of the inventory. The total cost as a function of replacement percentage is shown in Chapter 2.
- The Fort Jackson and Fort Leonard Wood cost studies compare favorably with the estimates presented in this report.

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APPENDIX A: FY89 and FY90 Red Book AC&R Inventory Data

Table A1

Technical Data Activity Code Definitions

TDAC	DESCRIPTION	UNITS
K15100	AIR COND AND CHILL WATER PLTS	TON CAP
K15111	AIR COND PLTS (>100 TNS)	TON CAP
K15112	AIR COND PLTS(26-100 TNS)	TON CAP
K15113	AIR COND PLTS (5-25 TNS)	TON CAP
K15114	CHILLED WATER PLTS (>100 TNS)	TON CAP
K15115	CHILLED WATER PLTS (25-100 TNS)	TON CAP
K15130	HEAT PUMP (> 5 TONS)	TON CAP
K15120	AIR COND PLTS (< 5 TNS)	TON CAP
K15140	HEAT PUMP (< 5 TONS)	TON CAP
K15220	COLD STORAGE PLT (INCL ICE MFG)	HP CAP
K15300	REFRIGERATION	HP CAP
K15211	REFRIGERATION (> 5 HP)	HP CAP
K15212	REFRIGERATION (< 5 HP)	HP CAP

Table A2

FY89 Red Book Air Conditioning and Refrigeration Totals

MAJOR COMMAND	AIR CONDITIONING (TONS)										REFRIGERATION (HP)		
	J51000	J52000	K15111	K15112	K15113	K15114	K15115	K15130	K15120	K15140	K15220	K15211	K15212
CORPS OF ENGRS	1,533		1,968										
HEALTH SERV CMD	36,297	890	19,512	277	472				7,273		890	2,863	1,232
MIL DIST OF WA	24,100	448	19,560	1,503	1,182				1,088	21	446	904	211
MIL TRAF MGT CMD	2,357	1,125	1,340	243	105				630	43	825	759	
FORCES CMD	240,666	20,922	111,385	25,667	20,355	9,490	829	1,431	64,915	82	7,055	17,583	7,501
ARMY EUROPE	12,221	6,021	19,236	68	3,184				3,418		4,189	16,760	1,807
SOUTHERN CMD	24,801	1,050	5,740	3,508	1,382	1,443	429		11,600		1,050	40	100
WESTERN CMD	403	860	15,816						2,762		1,550	1,827	
ARMY MTRL CMD	93,839	2,844	124,799						19,155		2,257	15,660	
US MILIT ACAD									660		593	693	
US ARMY JAPAN	7,656	149	6,397						3,685			761	
EIGHTH US ARMY	27,003	4,188	22,997						2,595		1,616	4,466	
INTEL & SEC CMD	594	68	2,442	541	60				600		41	137	63
TRNG & DOC CMD	268,071	3,870	143,783	35,825	53,686	1,647	2,181	2,834	81,512	8,323	4,492	22,638	5,069
INFO SYS CMD	7,743		3,650	2,095	2,236				887		25		2
TOTALS	747,284	42,435	498,625	69,727	82,662	12,580	3,439	4,265	200,780	8,469	25,029	85,091	15,985

Table A3

FY90 Red Book Air Conditioning and Refrigeration Totals

MAJOR COMMAND	AIR CONDITIONING (TONS)										REFRIGERATION (HP)		
	J51000	J52000	K15111	K15112	K15113	K15114	K15115	K15130	K15120	K15140	K15220	K15211	K15212
CORPS OF ENGRS	735	282	1,096	282	153								
HEALTH SERV CMD	36,411	890	19,497	286	472				7,393		890	2,863	1,232
MIL DIST OF WA	15,536	360	8,332	2,372	13,543				4,036	21	278	209	906
MIL TRAF MGT CMD	2,104	1,125	1,340	243	105				630	43	825	759	
FORCES CMD	216,233	16,195	131,780	31,703	22,451	1,096	658	1,311	65,813	3,956	5,498	18,780	9,283
ARMY EUROPE	1,914	4,673	19,443	508	2,135			334	5,337		1,824	12,984	4,465
SOUTHERN CMD	2,180	1,050	5,740	3,508	1,382	1,573	429		11,600		1,050	40	100
WESTERN CMD	18,495	1,757	15,794						2,701		59	1,960	
ARMY MTRL CMD	103,20	3,049	132,193						20,585		2,393	18,127	
US MILIT ACAD	6,222		6,161						660		693		
US ARMY JAPAN	10,917	250	6,832						4,085		149	798	
EIGHTH US ARMY	28,805	4,141	14,168						3,297		1,741	4,559	
INTEL & SEC CMD	587	68	500						87		68	112	
TRNG & DOC CMD	288,744	4,848	146,075	43,656	43,545	2,029	2,479	2,151	87,871	3,939	4,682	20,739	2,598
INFO SYS CMD	8,610	225	3,650	1,965	2,155				840		225		2
TOTALS	740,700	38,913	512,601	84,523	85,941	4,698	3,566	3,796	214,935	7,959	20,375	81,930	18,586

APPENDIX B: Army-wide Retrofit and Replacement Cost Calculations

Table B1

Estimated Refrigerant Usage in Air Conditioning Equipment

Refrigerant	*Fraction	x	Total lb†	=	Pounds
CFC-11	0.262		1,760,000		585,000
CFC-12	0.024		1,760,000		55,000
HCFC-22	0.612		1,760,000		895,000
CFC-113	0.003		1,760,000		5,000
R-500	0.098		1,760,000		218,000
R-502	0.001		1,760,000		2,000

* Source: Sohn, Homan, and Sliwinski.

† Calculated from FY89 Red Book data.

Table B2

Estimation of No. of Units Using CFC Refrigerants

Refrigerant	lb refrig	+	(Avg. size	x	lb/ton)	=	No. units
CFC-11	585,000		550 tons		2.2		484
CFC-12	55,000		800 tons		2.2		32
CFC-113	5,000		220 tons		2.2		11
R-500	218,000		1300 tons		2.2		77

Table B3

Large Air-Conditioning Unit Age Summary

Age	Fraction	Percentage
≤ 10 years	18/24	75%
> 10 years	6/24	25%

* Source: Sohn, Homan, and Sliwinski.

Table B4

Estimated Retrofit and Replacement Costs for Air-Conditioning Equipment

Replacement Costs (Units > 10 years old)

<u>Existing Unit</u>					
<u>Size</u>	<u>Refrig.</u>	<u>No. units</u>	x	<u>Cost/unit</u>	= <u>Cost (millions)</u>
550 tons	CFC-11	95		1.5 x \$170,000	\$24.23
800 tons	CFC-12	6		1.5 x \$240,000	\$2.16
220 tons	CFC-113	11		1.5 x \$75,000	\$1.24
1300 tons	R-500	15		1.5 x \$325,000	\$7.31
<u>Replacement Costs =</u>					\$34.94

Retrofit Costs (Units ≤ 10 years old)

<u>Existing Unit</u>					
<u>Size</u>	<u>Refrig.</u>	<u>No. units</u>	x	<u>Cost/unit</u>	= <u>Cost (millions)</u>
550 tons	CFC-11	286		\$35,000	\$10.01
800 tons	CFC-12	18		\$65,000	\$1.17
1300 tons	R-500	45		\$85,000	\$3.83
<u>Retrofit Costs =</u>					\$15.01

Total Cost = Replacement Costs + Retrofit Costs = \$50.0 million

Table B5

Cold Storage and Refrigeration Capacities

	<u>Capacity</u>
Cold Storage (including ice mfg.)	25,000 hp
Refrigeration	101,000 hp

* Source: FY89 Red Book.

Table B6
Breakdown of Refrigeration Capacity

	Fraction	x	Overall cap.	=	Fractional cap.
Large refrig. units (>5 hp)	0.106		101,000 hp		10,700 hp
Small refrig. units (<5 hp)	0.126		101,000 hp		12,700 hp
Household refrigerators	0.768		101,000 hp		77,600 hp

* Source: Sohn, Homan, and Sliwinski.

Table B7
Estimation of Capacity by Refrigerant Type

<i>Refrigeration Units (Capacity < 5 hp)</i>					
<u>Refrigerant</u>	<u>Fraction</u>	x	<u>Total Capacity</u>	=	<u>Estimated Capacity</u>
CFC-12	0.792		12,700 hp		10,000 hp
HCFC-22	0.020		12,700 hp		300 hp
R-502	0.188		12,700 hp		2,400 hp
<i>Refrigeration Units (Capacity > 5 hp)</i>					
<u>Refrigerant</u>	<u>Fraction</u>	x	<u>Total Capacity</u>	=	<u>Estimated Capacity</u>
CFC-12	0.384		10,700 hp		4,100 hp
HCFC-22	0.171		10,700 hp		1,800 hp
R-502	0.445		10,700 hp		4,800 hp
<i>Cold Storage (including ice mfg.)</i>					
<u>Refrigerant</u>	<u>Fraction</u>	x	<u>Total Capacity</u>	=	<u>Estimated Capacity</u>
CFC-12	0.853		25,000 hp		21,300 hp
HCFC-22	0.073		25,000 hp		1,800 hp
R-502	0.074		25,000 hp		1,900 hp

* Source: Sohn, Homan, and Sliwinski.

Table B8

Estimation of Number of Units by Refrigerant Type

<i>Refrigeration Units (Capacity < 5 hp)</i>				
<u>Refrigerant</u>	<u>Capacity</u>	x	<u>Capacity/unit*</u>	= <u>Estimated No.of Units</u>
CFC-12	10,100 hp		2.5 hp	4,035
HCFC-22	255 hp		2.5 hp	102
R-502	2,395 hp		2.5 hp	958
<i>Refrigeration Units (Capacity > 5 hp)</i>				
<u>Refrigerant</u>	<u>Capacity</u>	x	<u>Capacity/unit*</u>	= <u>Estimated No.of Units</u>
CFC-12	4,120 hp		7.5 hp	549
HCFC-22	1,835 hp		7.5 hp	244
R-502	4,770 hp		7.5 hp	636
<i>Cold Storage (including ice mfg.)</i>				
<u>Refrigerant</u>	<u>Capacity</u>	x	<u>Capacity/unit*</u>	= <u>Estimated No.of Units</u>
CFC-12	21,300 hp		35.0 hp	610
HCFC-22	1,800 hp		35.0 hp	52
R-502	1,900 hp		35.0 hp	53

* These are the average sized units for the category (Sohn, Homan, and Sliwinski).

Table B9

Refrigeration Unit Age Summary

<u>Age</u>	<u>Fraction</u>	<u>Percentage</u>
≤ 10 years	1649/1788	90%
> 10 years	139/1788	10%

* Source: Sohn, Homan, and Sliwinski.

Table B10

Estimation of Retrofit/Replacement Costs for Refrigeration Units

Replacement Costs*Refrigeration Units (Capacity < 5 hp)*

<u>Refrigerant</u>	<u>No. of Units</u>	x	<u>Cost/unit*</u>	=	<u>Estimated Cost (mill.)</u>
CFC-12	403		\$4,500		\$1.82
R-502	958		\$4,500		\$4.31

Refrigeration Units (Capacity > 5 hp)

<u>Refrigerant</u>	<u>No. of Units</u>	x	<u>Cost/unit*</u>	=	<u>Estimated Cost (mill.)</u>
CFC-12	55		\$7,500		\$0.41
R-502	636		\$7,500		\$4.77

Cold Storage (including ice mfg.)

<u>Refrigerant</u>	<u>No. of Units</u>	x	<u>Cost/unit*</u>	=	<u>Estimated Cost (mill.)</u>
CFC-12	61		\$30,000		\$1.83
R-502	53		\$30,000		\$1.59
<u>Replacement Cost =</u>					\$14.7million

Retrofit Costs*Refrigeration Units (Capacity < 5 hp)*

<u>Refrigerant</u>	<u>No. of Units</u>	x	<u>Cost/unit*</u>	=	<u>Estimated Cost (mill.)</u>
CFC-12	3,632		\$1,500		\$5.45

Refrigeration Units (Capacity > 5 hp)

<u>Refrigerant</u>	<u>No. of Units</u>	x	<u>Cost/unit*</u>	=	<u>Estimated Cost (mill.)</u>
CFC-12	494		\$2,500		\$1.23

Cold Storage (including ice mfg.)

<u>Refrigerant</u>	<u>No. of Units</u>	x	<u>Cost/unit*</u>	=	<u>Estimated Cost (mill.)</u>
CFC-12	549		\$10,000		\$5.49
<u>Replacement Cost =</u>					\$12.2 million

Total Cost = Replacement Costs + Retrofit Costs = \$26.9 million

* The cost/unit information has been obtained from equipment suppliers.

ABBREVIATIONS AND ACRONYMS

AC	air-conditioning
AC&R	air-conditioning and refrigeration
AMC	U.S. Army Materiel Command
ARI	Air-Conditioning and Refrigeration Institute
ASA	Assistant Secretary of the Army
CFC	chlorofluorocarbon
DEH	Directorate of Engineering and Housing
DOD	Department of Defense
FORSCOM	U.S. Army Forces Command
FY	Fiscal Year
HCFC	hydrochlorofluorocarbon
HQDA	Headquarters, Department of the Army
LTR	letter
TR	technical report
TRADOC	U.S. Army Training and Doctrine Command
USACERL	U.S. Army Construction Engineering Research Laboratories
USAEHSC	U.S. Army Engineering and Housing Support Center
UV	ultraviolet

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